MEBT Absorber Prototype Testing Update

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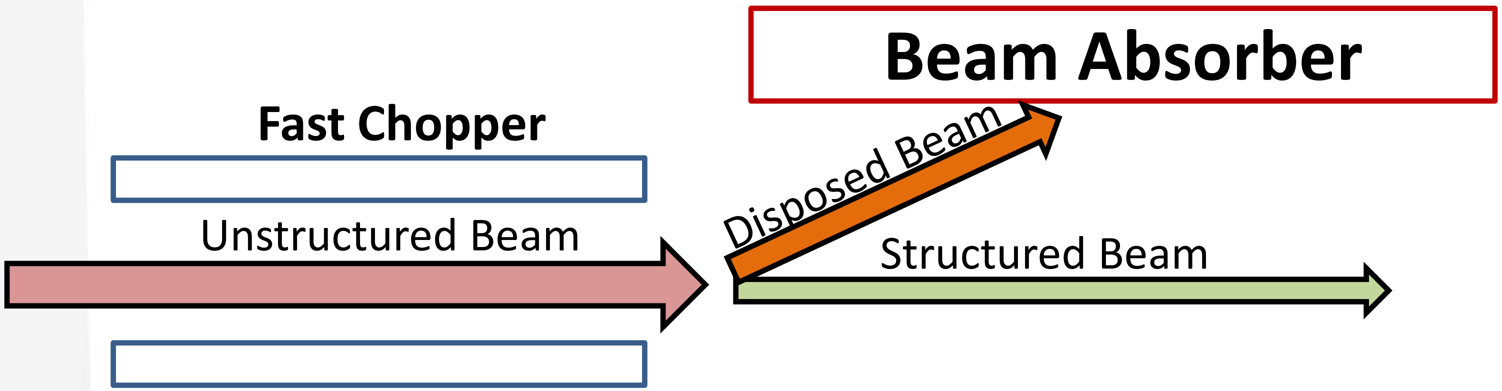
C. Baffes, B. Hanna, K. Reader, A. Shemyakin

PX Doc DB ID: Project X-doc-1320

MEBT Prototype Absorber Update

- Background
- Prototype 2 Design
- Test Results
- Conclusions and Implications to PXIE Design

Background: Absorber Configuration



Functional Specifications Document:

https://projectx-docdb.fnal.gov:440/cgi-bin/ShowDocument?docid=964

Key Driving Absorber Requirements

- 2.1MeV Ions
- 21kW maximum incident power (~75% absorbed / ~25% reflected)
- Beam size: $\sigma_x = \sigma_y = 2$mm
- 650mm maximum length

Key Derived Parameters

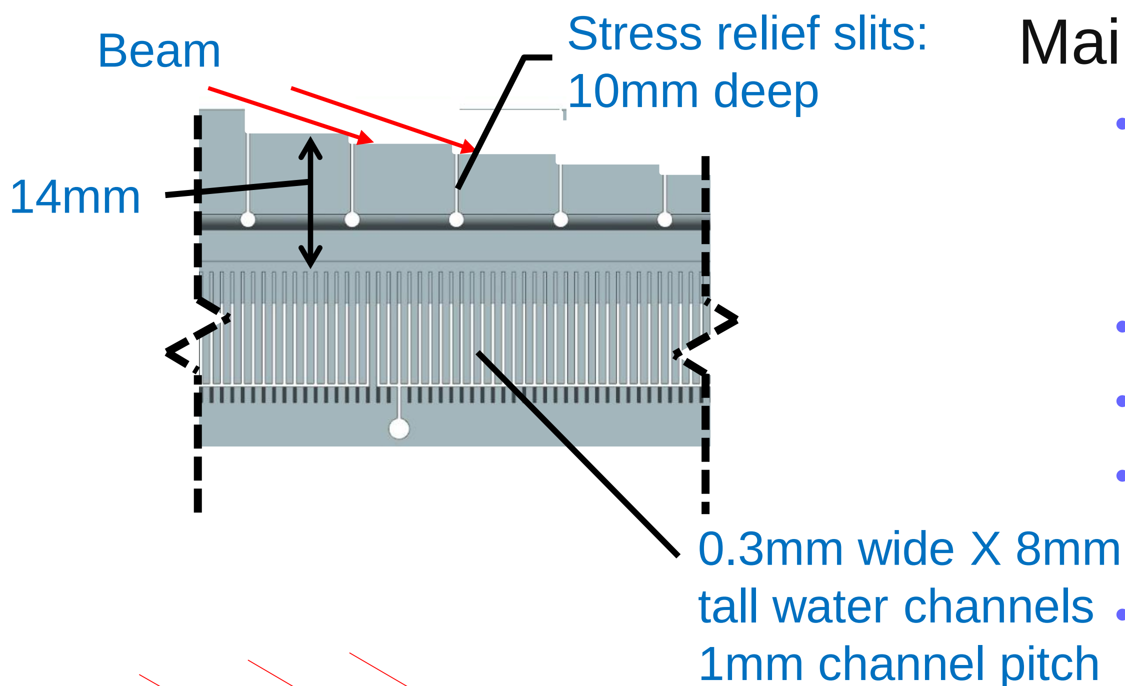
- 0.029rad grazing angle
- ~17 W/mm^2 maximum absorbed power density of the face of the absorber

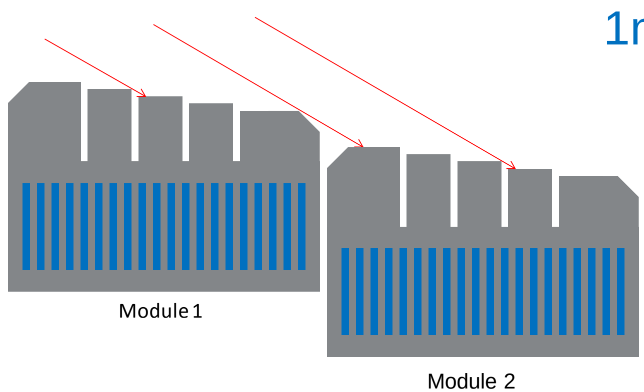
Design History

- Design has been evolving for the past few years
  - Initial concept for Cu absorber (Hassan/Lebedev)
  - All-Mo-TZM absorber to resist blistering
  - TZM/Al thermal contact design

- Prototypes were built and tested in an electron test beam
  - Walton “Pre-Prototype” – better than expected thermal contact
  - All-TZM Prototype 1 – met PXIE requirements, tricky fabrication
  - Prototype 2 – meets PXIE requirements, subject of this report

2011 Preliminary
PXIE and Prototype 1 Concept





Vertical scale greatly exaggerated

Main design features

- Grazing incident angle of 29 mrad to decrease the surface power density
- TZM to address blistering
- Stress relief slits
- Steps to shadow the slits from beam
- narrow transverse channels for water cooling
- The total ~0.5m length divided to 4 identical modules to simplify manufacturing

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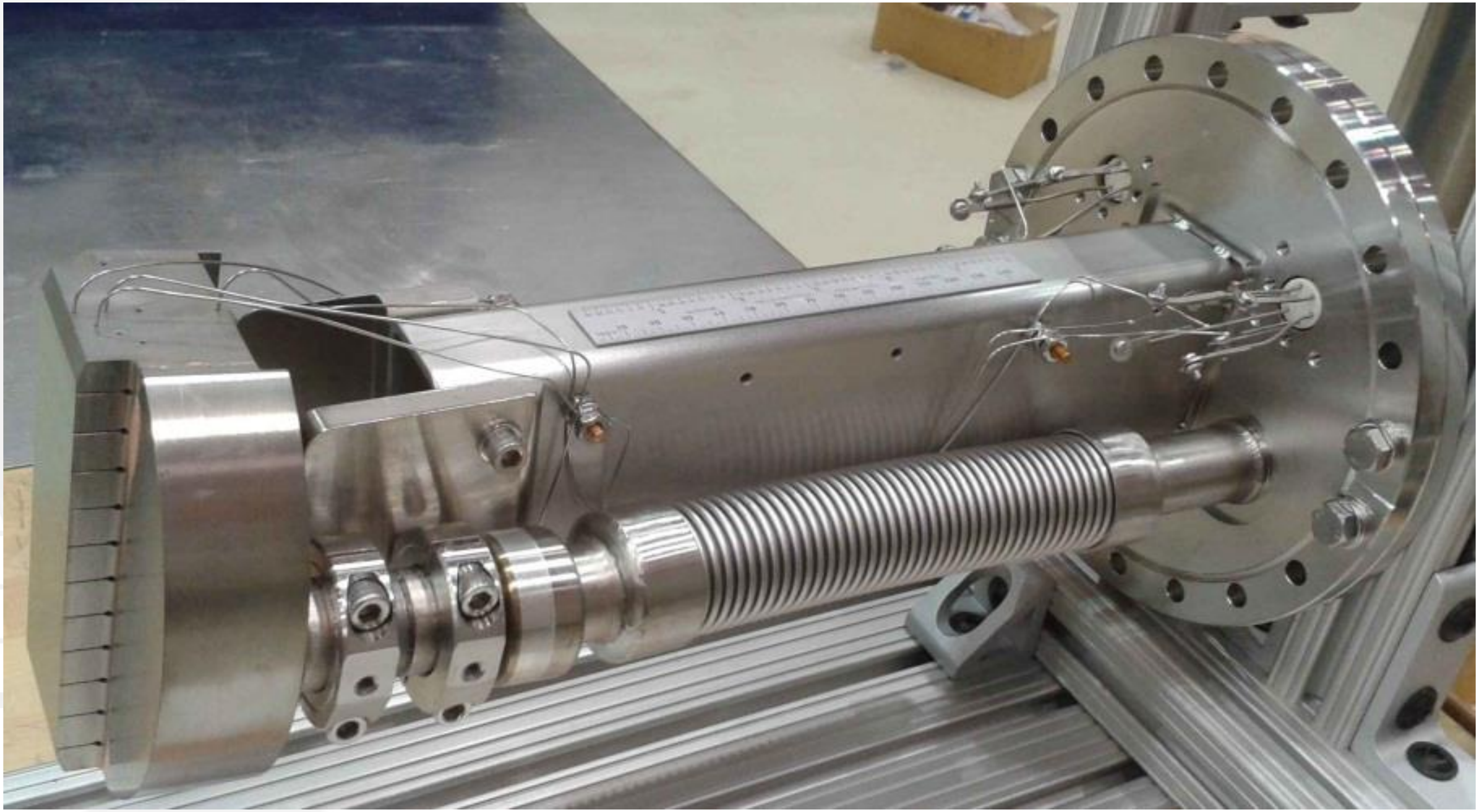
Prototype 1 Absorber



Fermilab

2011 Concept Design Risks

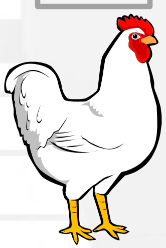
Key risks of the specific design included:

- Manufacturing processes
  - Machining of Mo TZM
  - TZM-to-stainless transition
- Flow characteristics and heat transfer
- High temperatures in absorber material
- Module-to-module and global alignment stability
- Blistering/Sputtering of TZM material in H- Beam

Addressed by Prototype I testing

Goals of Prototype I Testing

- Investigate areas of fabrication risk
- Study OTR as a diagnostic technique
- **Test ability to survive expected power density**



- Test ability of absorber to survive thermal cycling
- Correlate temperatures to improve modeling
- Investigate cooling performance in different flow regimes

Prototype 1 Conclusions: Analysis/Capability/Durability

The Good…

- The prototype survived 17 W/mm^2 average, 40 W/mm^2 peak
  - This meets requirement for PXIE @ 10mA (17 W/mm^2 peak)
- The absorber survived a modest number (~1E2) of thermal cycles
- Independent temperature measurements and estimates coincide within reasonable error bars

The Bad…

- We did not know whether we should be worried about the observed changes on the absorber surface

…And the Ugly

- We were afraid to do the planned thermal cycling tests. A coolant-to-vacuum leak will kill the test bench, precluding any further testing
- This is an even bigger fear for PXIE

Design Philosophy for PXIE Absorber

- Use the following tested design features
  - TZM material
  - Stair-step surface geometry for stress relief and shadowing
  - mm-scale cooling channel geometry
  - Graphite thermal interface layer with compressive preloading
- Design to accomplish the following:
  - Reduce the likelihood of water-to-vacuum failure mode by going to a non-monolithic thermal contact design
    - Failure of TZM less likely to propagate
    - Fab complex cooling features in a conventional material
  - Capture some of the reflected energy at the absorber
    - Minimize area of vacuum enclosure that needs blistering-resistant and/or actively cooled features

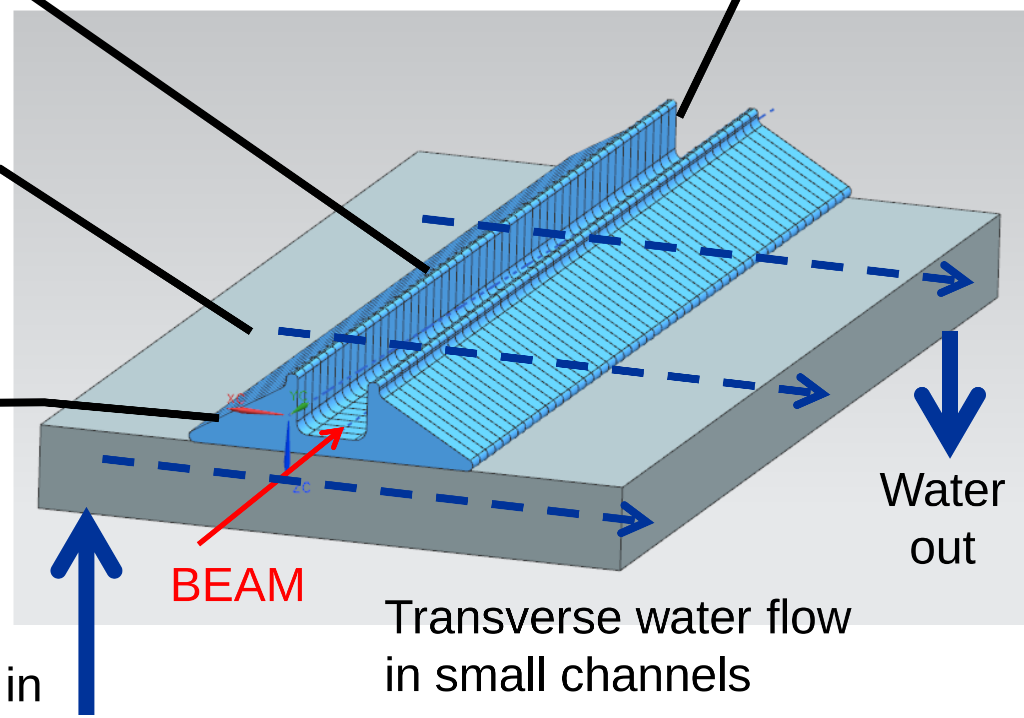
PXIE Absorber Cartoon

TZM absorbing fins
1cm thick
Stack Qty. ~50 of these
Beam incident in “valley”

Side walls absorb some
of the reflected energy
and shadow structure

Cooling Strongback
Same channel design
as prototype 1

(Not shown) Preload structure
Pushes individual TZM fins down
into graphite thermal interface



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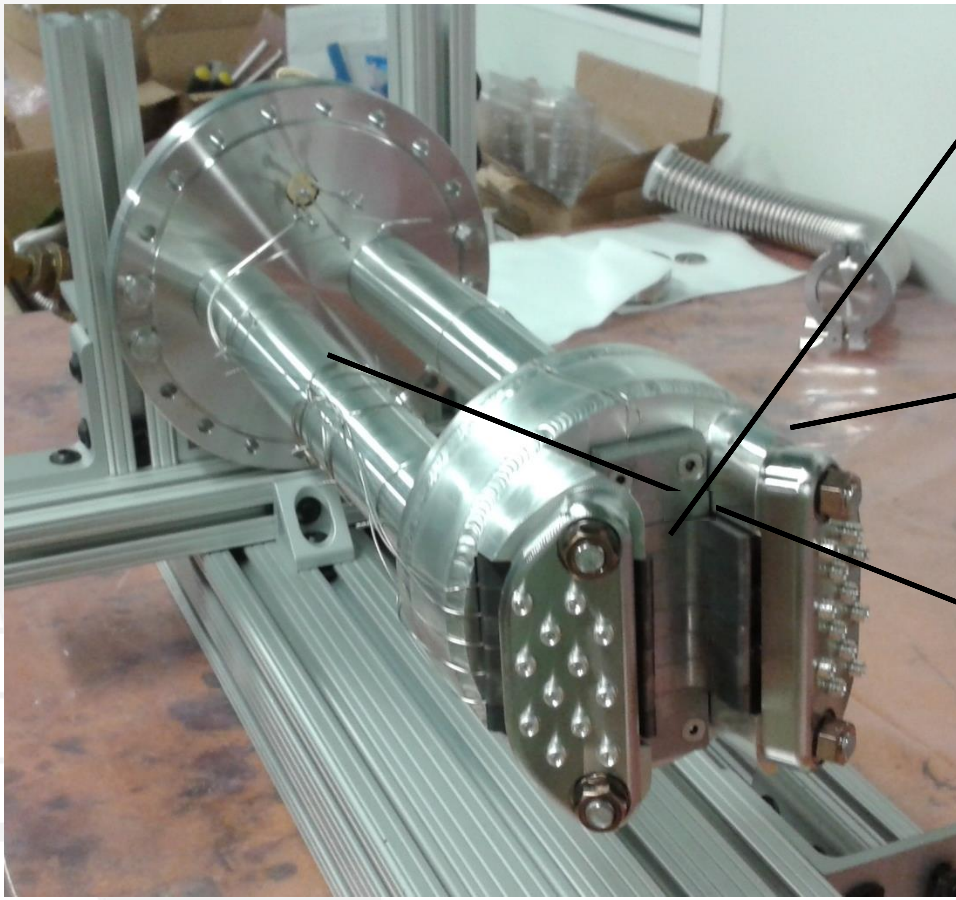
- Background
- Prototype 2 Design
- Test Results
- Conclusions and Implications to PXIE Design

Prototype 2

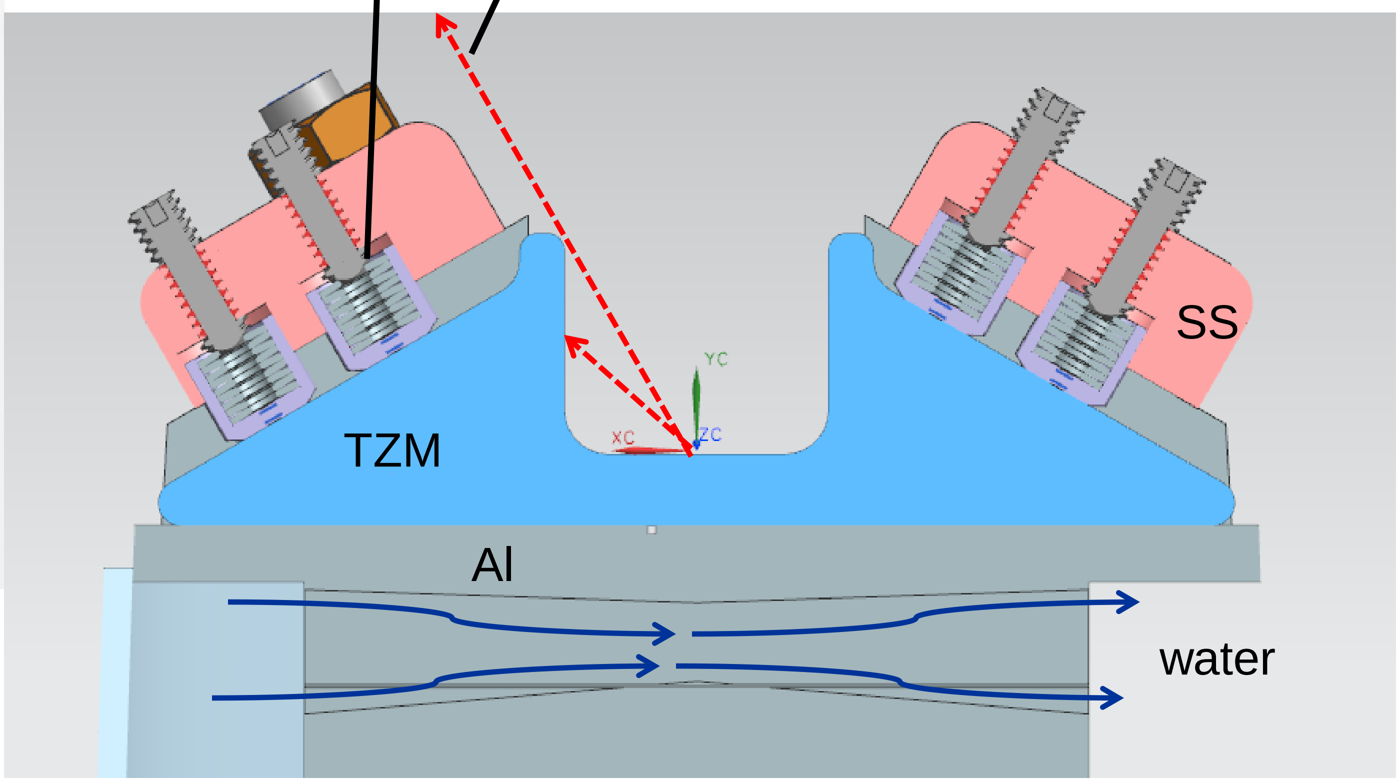


- 6 PXIE-like TZM fins
  - Graphite thermal contact
  - Individually preloaded
- Aluminum cooling strongback
  - Transverse cooling channels
- Aluminum plumbing to air
  - No in-vacuum material transitions

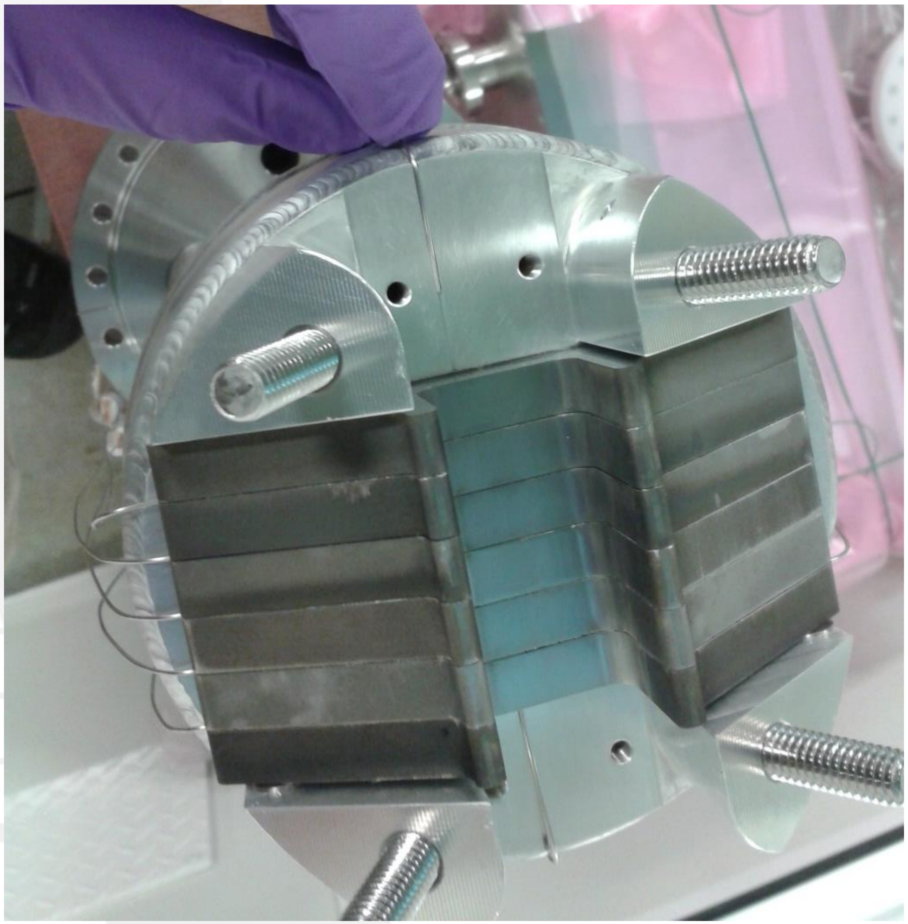
Prototype 2 Cross Section

Compliant preloading with disk springs

Structure (mostly) shielded from reflected energy by TZM



Prototype 2
Thermocouple Implementation



- Dia. 750μm thermocouples sandwiched between TZM fins
- Accuracy of reading relies on low longitudinal thermal gradients
  - True in PXIE
  - Not true in prototype test
- We were plagued by thermal contact problems with this scheme

Current Concept Design Risks

Un-retired risks included:

- Is the thermal contact "good enough"?
- Expected higher temperatures than prototype 1: is this survivable?
- Can the brittle material survive thermal cycling?

Addressed by Prototype 2 testing

- Blistering/Sputtering of TZM material in H- Beam (can't be retired until PXIE)
  - But emittance scanner and LEBT chopper will provide clues

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- **Test Results**
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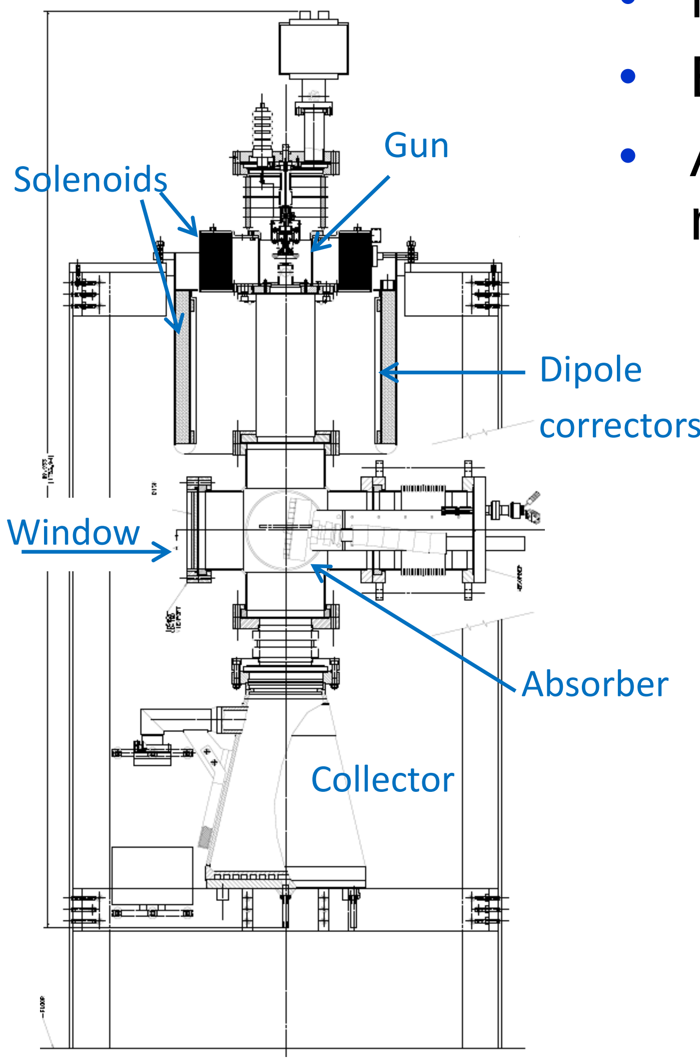
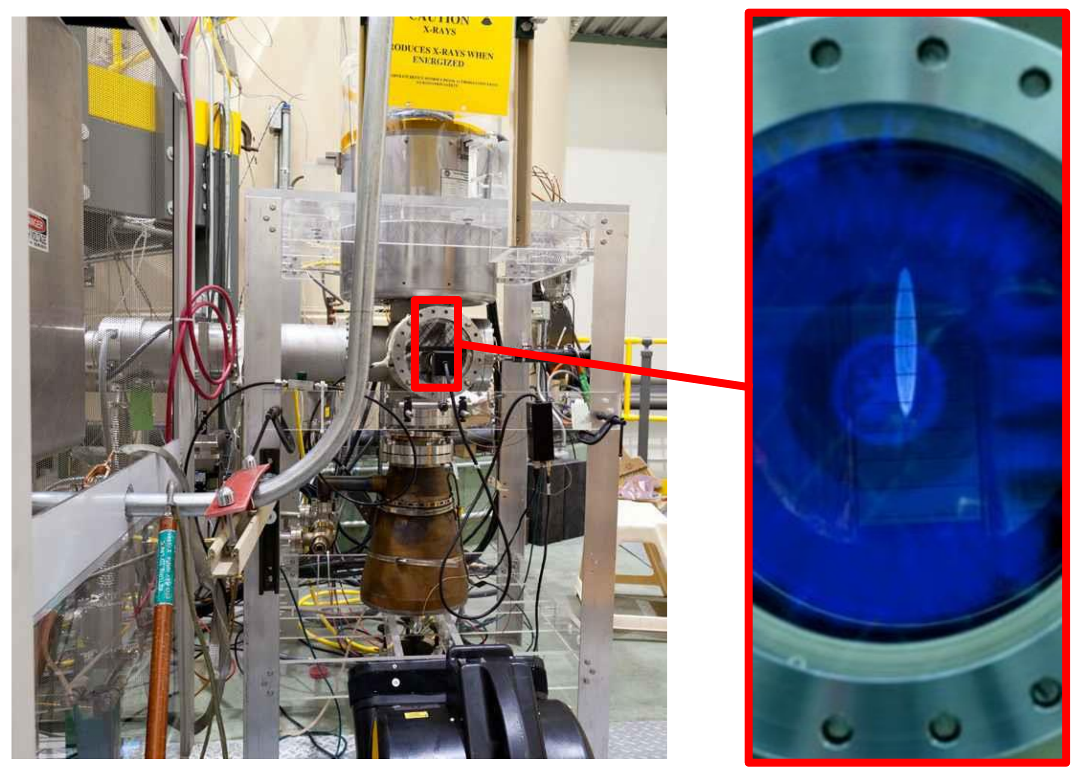
Test bench

- Mainly parts from ECool project
- E-beam: 27.5 keV, up to 200mA, 5.5kW max
- Absorber and scraper prototypes may be moved into the beam





Test Implementation: K. Carlson, B. Hanna, L. Prost, J. Walton

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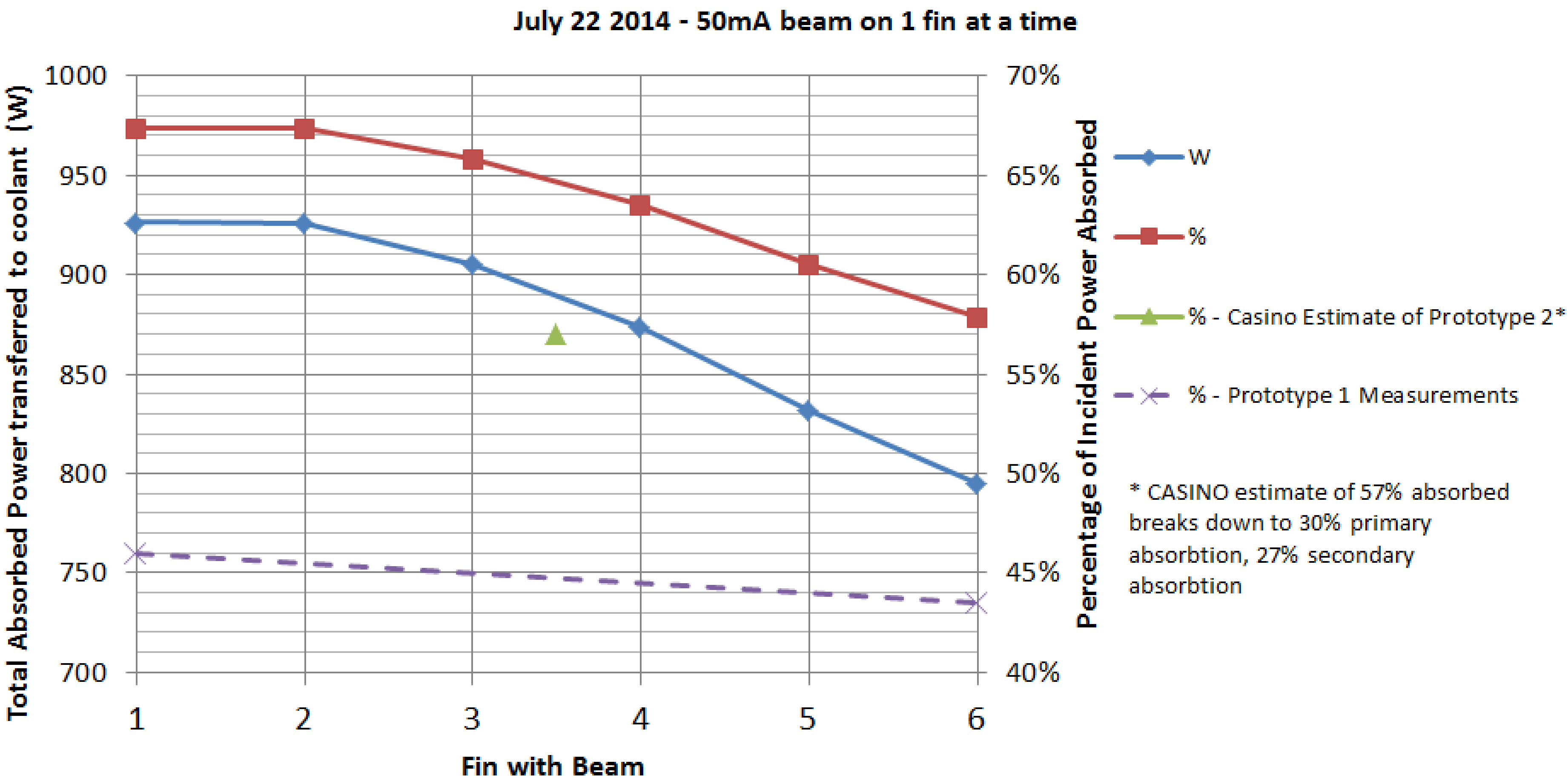
Power Deposition

- A large fraction of the power incident on the absorber is removed by secondary particles (“reflected”)
- Absorbed power can be calculated from water temperature rise and flow rate
- Result: ~65% of incident e- beam power is absorbed
  - Higher than prototype 1 value of ~44% due to absorption of some secondary particles on side-wall surfaces
  - Strong dependence on beam position due to geometry of “reflected” particles

Power deposition



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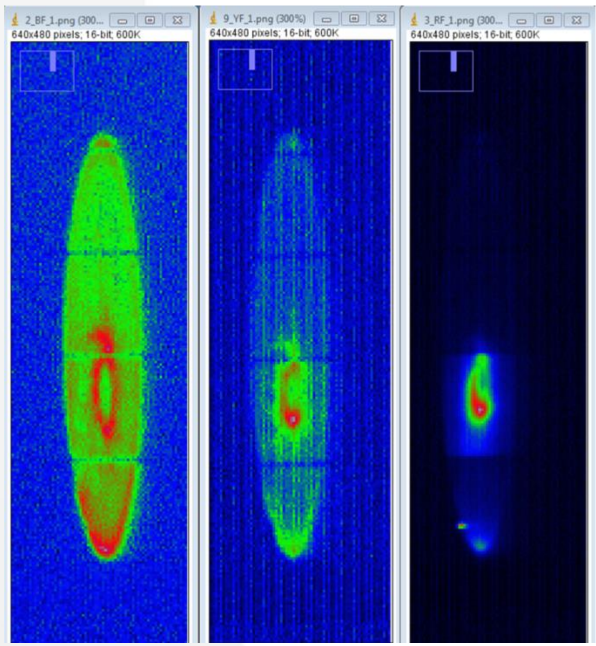
Optical Measurement of Surface Temperatures

B Y R



Images of the beam footprint with different filters, in false colors. Color/intensity map differs between images.

- Using methods exercised in testing of previous prototype testing, surface temperatures were estimated from light
  - Blue-filtered image dominated by OTR except at highest power densities
  - Red and Yellow filter images dominated by thermal radiation
  - Images can be used together to estimate temperature profiles

Peak Test Power Density
“Mode 4” – 23 W/mm^2 average

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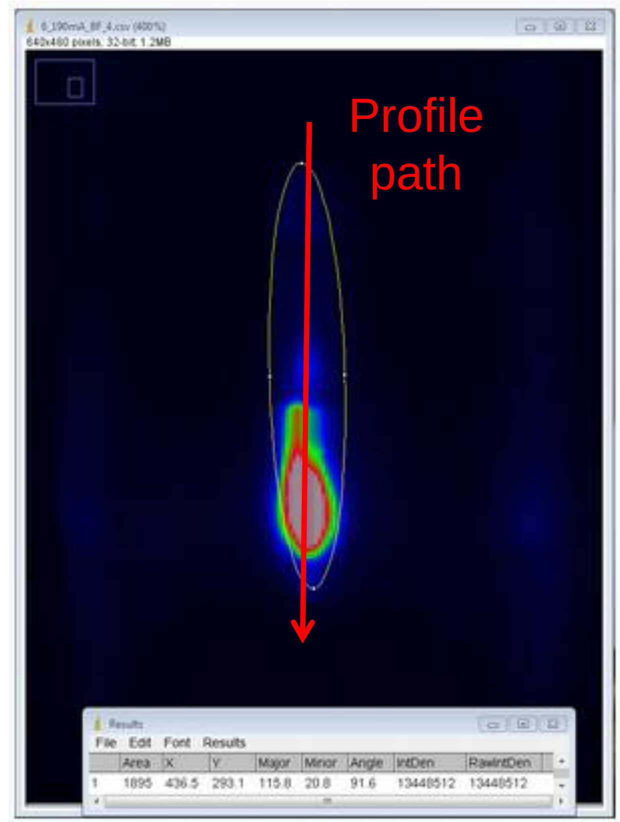
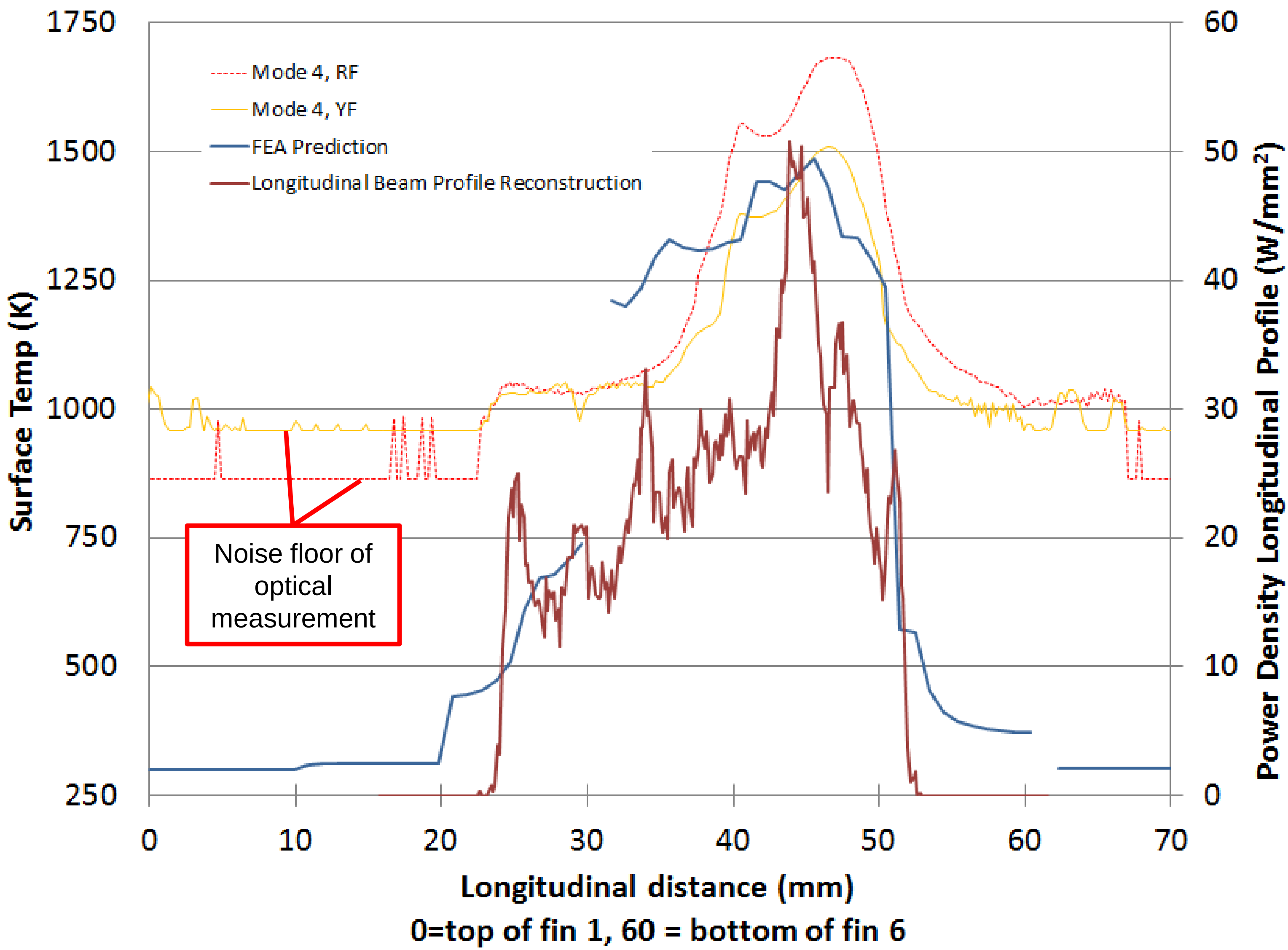
- Images of thermal radiation were recorded with combinations of red, yellow and neutral density filters (for dynamic range)
- The Blue-filter image was used to understand the size of the beam footprint via OTR
- Temperatures were measured optically and with thermocouples
- Finite element model run with equivalent beam power condition (but beam profile scaled from a larger beam with no thermal radiation in the blue image)
- Average power density over beam profile 23W/mm^2 - ~1.3X Expected PXIE peak

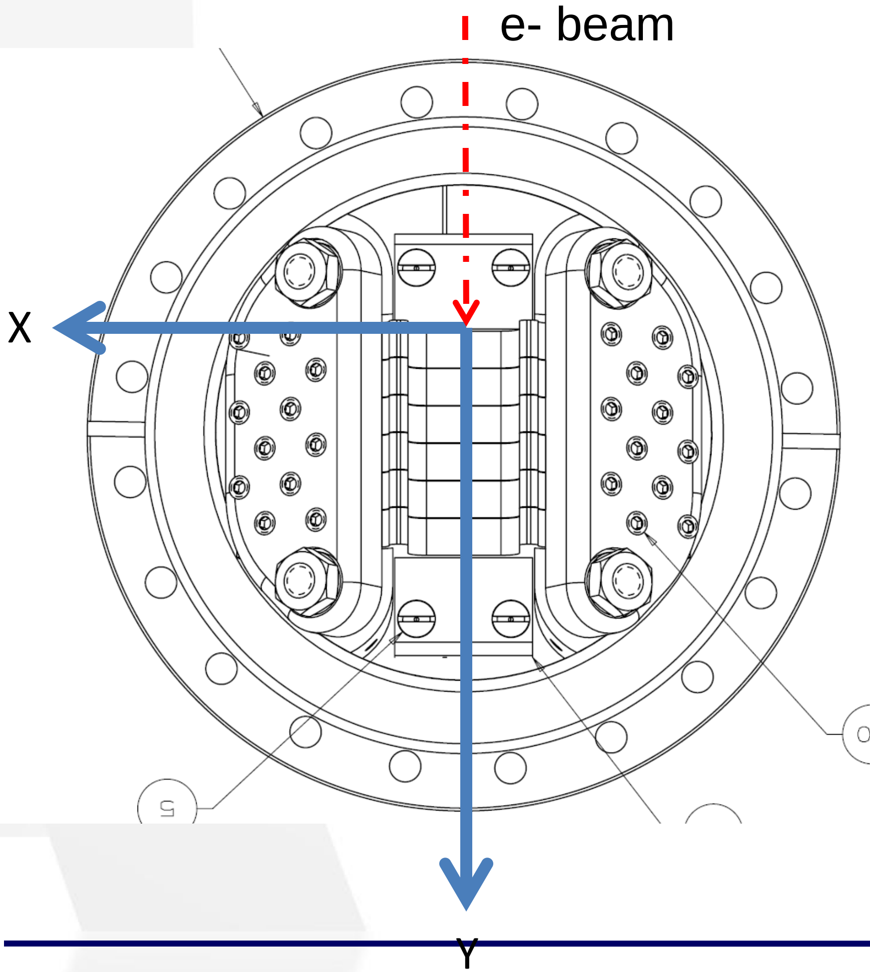


Blue image in false colors. The ellipse drawn in ImageJ shows the area used for calculating the average power density.

Surface Temperature Profile
T_{max} < 1700K



Thermocouple Locations



TC	X (mm)	Y (mm)	Z (mm)
TC01	5	10	-3.2
TC02	5	20	-3.2
TC03	5	40	-3.2
TC04	5	50	-3.2
TC05	-5	50	-3.2
TC06	5	60	-8.6

TC01-TC05 are sandwiched between TZM fins

TC06 is at the TZM/Aluminum interface

Thermocouple Correlation Results

- Prediction quality is not good – FEA prediction up to ~30% off from measurement (after tuning of FEA model)
- Measurement quality is poor due to uncertainties about thermocouple contact and axial conduction

		Focusing Mode 1 : Least Focused		Focusing Mode 2		Focusing Mode 3		Focusing Mode 4: Most Focused	
		Predicted	**Measured**	**Predicted**	**Measured**	**Predicted**	**Measured**	**Predicted**	**Measured**
Tmax TZM (C)		516		604		832		1213	
Tmax AL (C)		129		144		171		192	
TC01	**dT above water (C)**	70	55	48	36	20	17	13	10
	prediction error	27%		32%		13%		37%	
TC02	**dT above water (C)**	136	100	140	92	109	76	66	40
	prediction error	36%		53%		44%		66%	
TC03	**dT above water (C)**	197	159	228	207	288	256	365	295
	prediction error	24%		10%		13%		24%	
TC04	**dT above water (C)**	170	160	178	161	191	156	215	161
	prediction error	6%		10%		23%		33%	
TC05	**dT above water (C)**	190	194	193	197	195	183	220	179
	prediction error	-2%		-2%		7%		23%	
TC06	**dT above water (C)**	35	42	27	30	23	27	19	26
	prediction error	-18%		-9%		-15%		-25%	

prediction error calculated as (predicted - measured) / measured

however, measured values are clouded by systematic measurement errors (e.g. contact and conduction effects)

Quality of Graphite Thermal Contact

- Thermocouple and optical temperature measurements were used to tune up the FEA model
- As shown on previous slides, agreement is not perfect
- However, this correlation is adequate to allow us to make an estimate of graphite thermal contact

- Best-fit value for graphite thermal contact conductance is 2E4 W/m^2K
  - This is quite good for contact in a vacuum
  - Maximum dT across interface under PXIE-like conditions is predicted to be 200K – not a large driver w.r.t. overall ~1500K peak temps
  - “Perfect” thermal contact, limited only by thermal conductivity through the graphite layer, would be 6E4 W/m^2K

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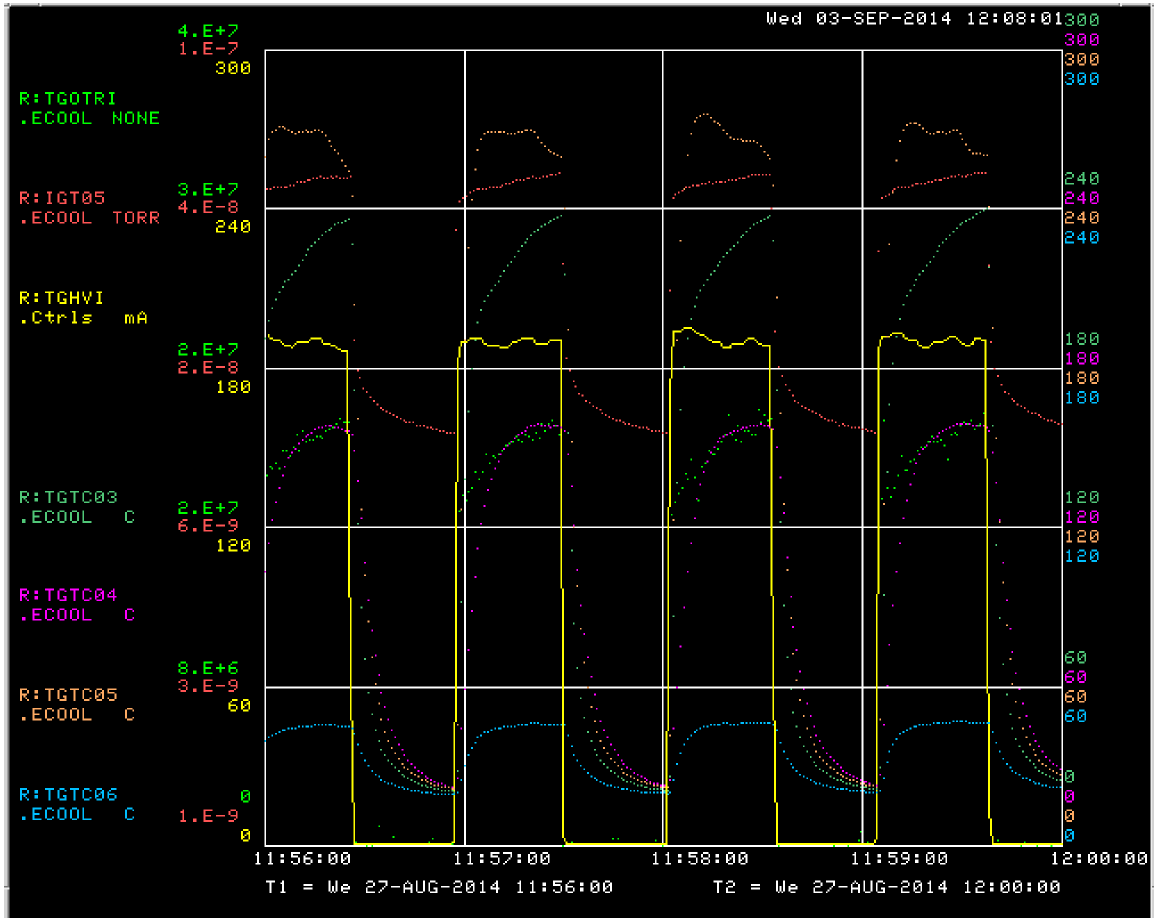
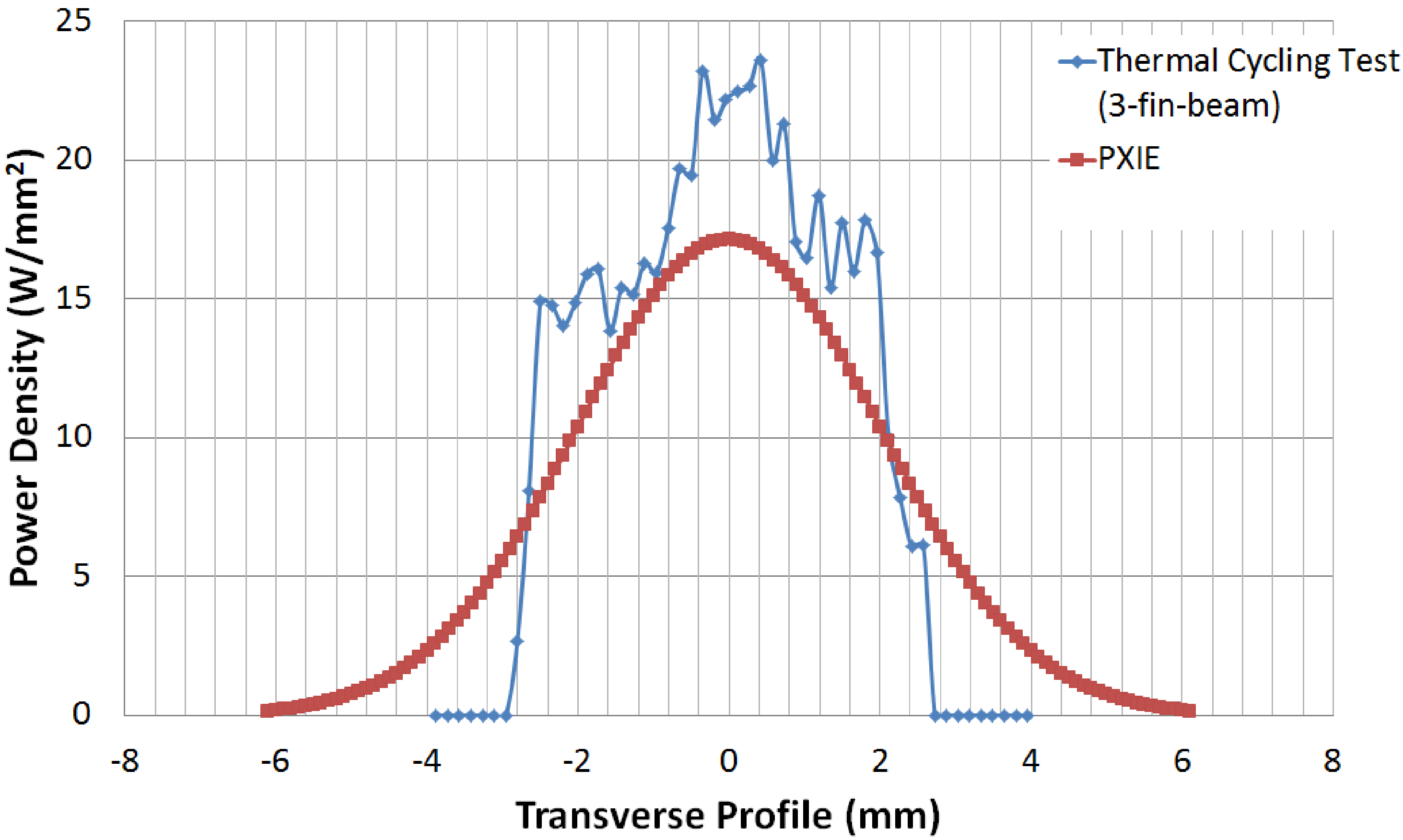
Thermal Cycling Test

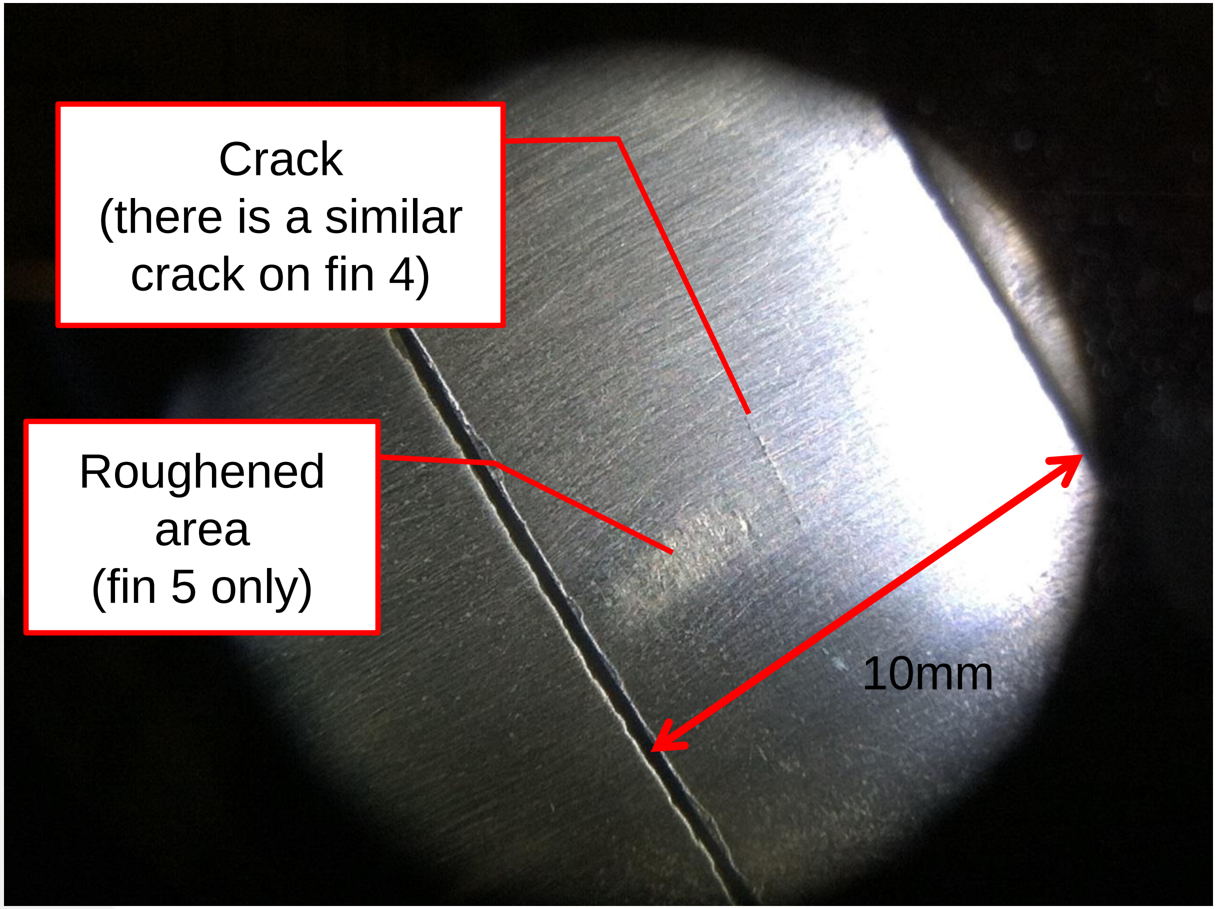
- The Prototype was subjected to thermal cycling to the FRS limit (>10K cycles) over a period of 8 days
- Short cycle period (30s on, 30s off) to limit deflections of test stand
- Absorber survived, but surface did exhibit some wear and tear



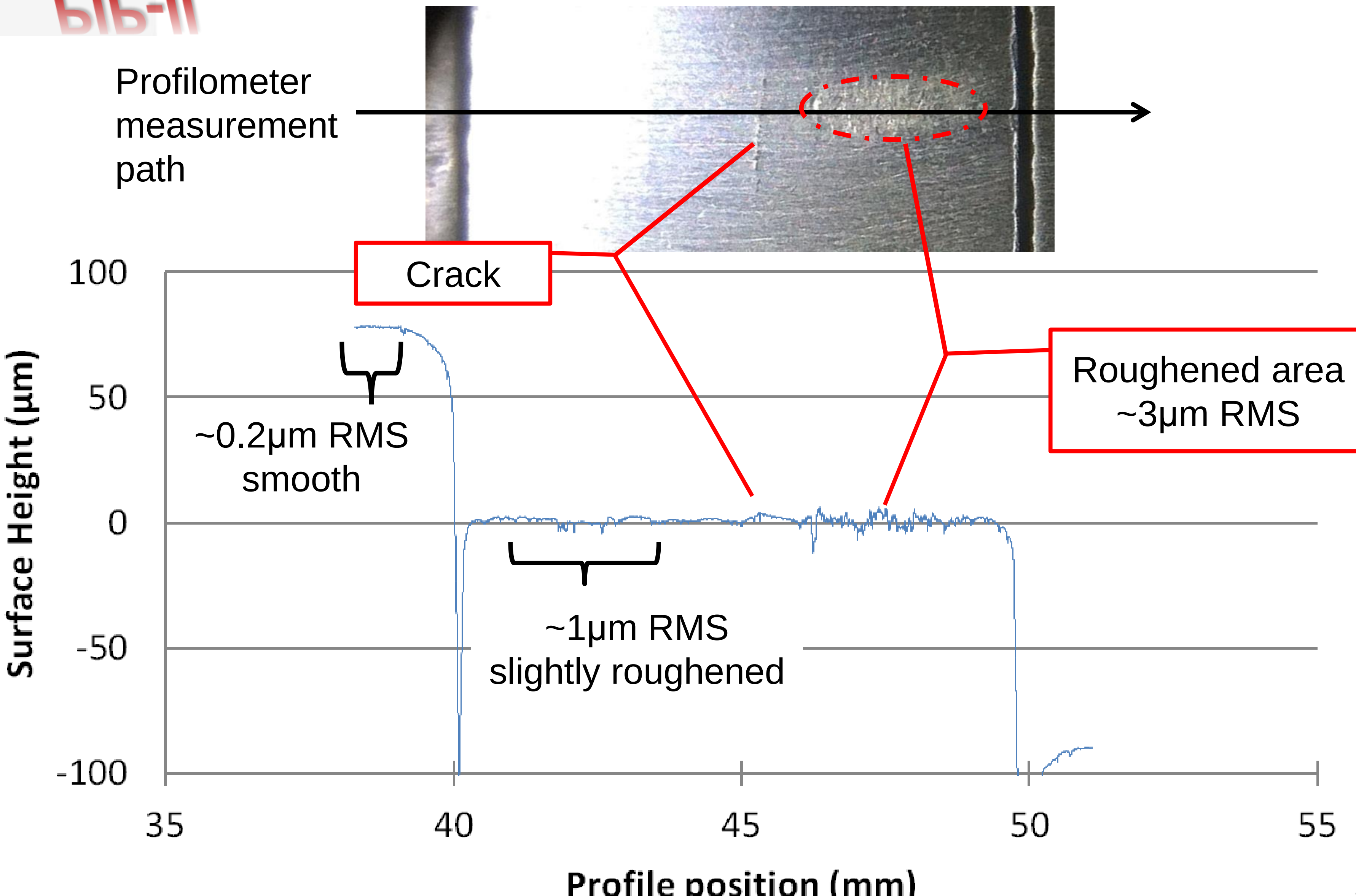
Transverse Beam Profile Thermal Cycling Condition vs. PXIE



Surface damage on Fin 5 After Thermal Cycling



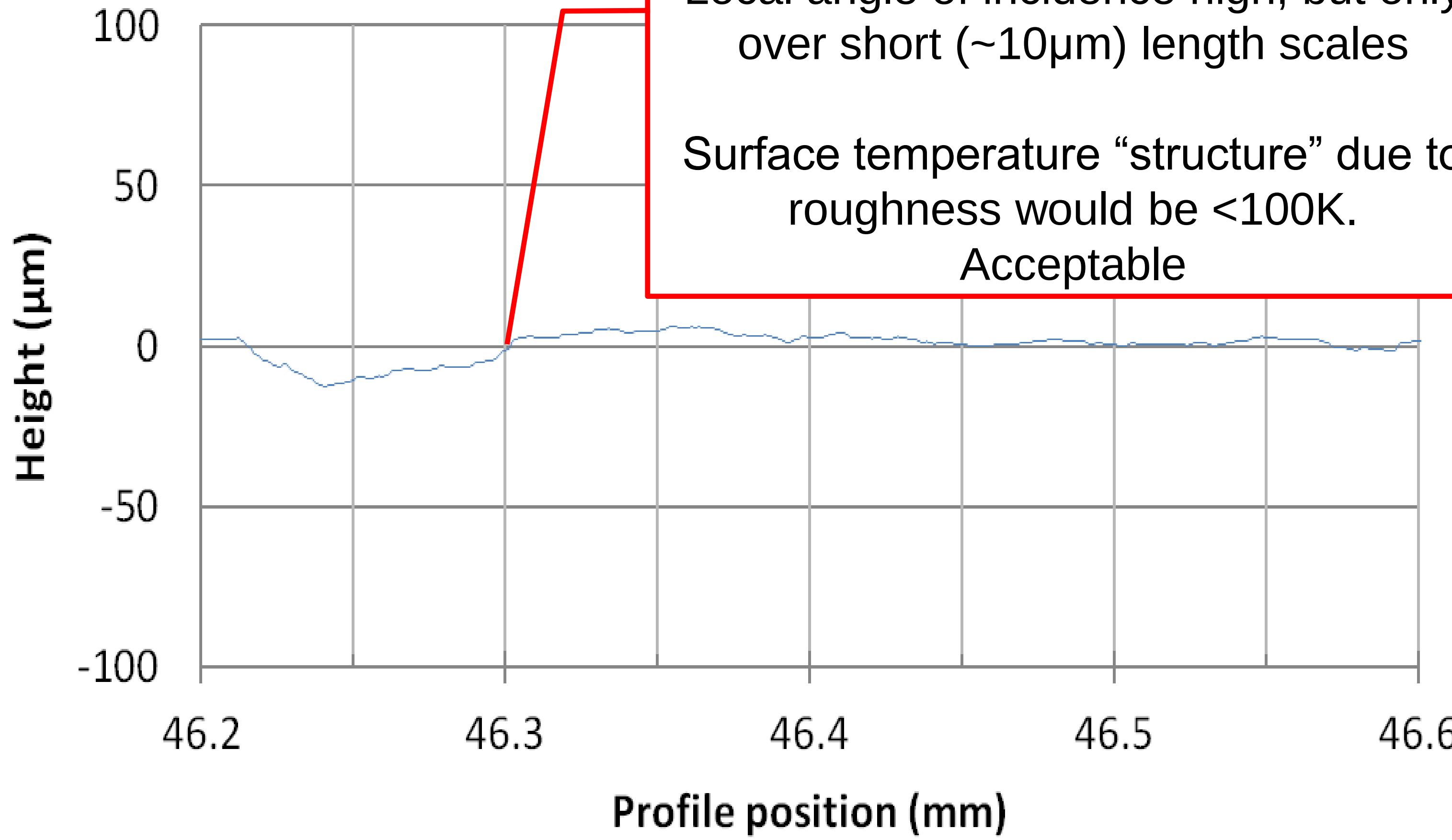
Surface After Thermal Cycling



Roughest Area
In Proportional Scale

Local angle of incidence high, but only over short (~10µm) length scales

Surface temperature “structure” due to roughness would be <100K. Acceptable



Thoughts on Surface Wear

- Concerns
  - Surface modification never desirable
  - PXIE will be more sensitive to surface slopes due to lower angle of incidence (29 mrad PXIE vs. ~130mrad Test Stand)
- However, this should be mitigated by the following
  - Surface cracks are all transverse – no impact on heat transfer
  - Small length scale of the roughness limits thermal impact
  - We expect surface “polishing” by sputtering - 100s of μm removed over the life of the absorber
  - Roughened area likely exposed to higher-than-design power density during thermal cycling
  - We conclude that this is not a show-stopper

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Conclusions of Testing Program

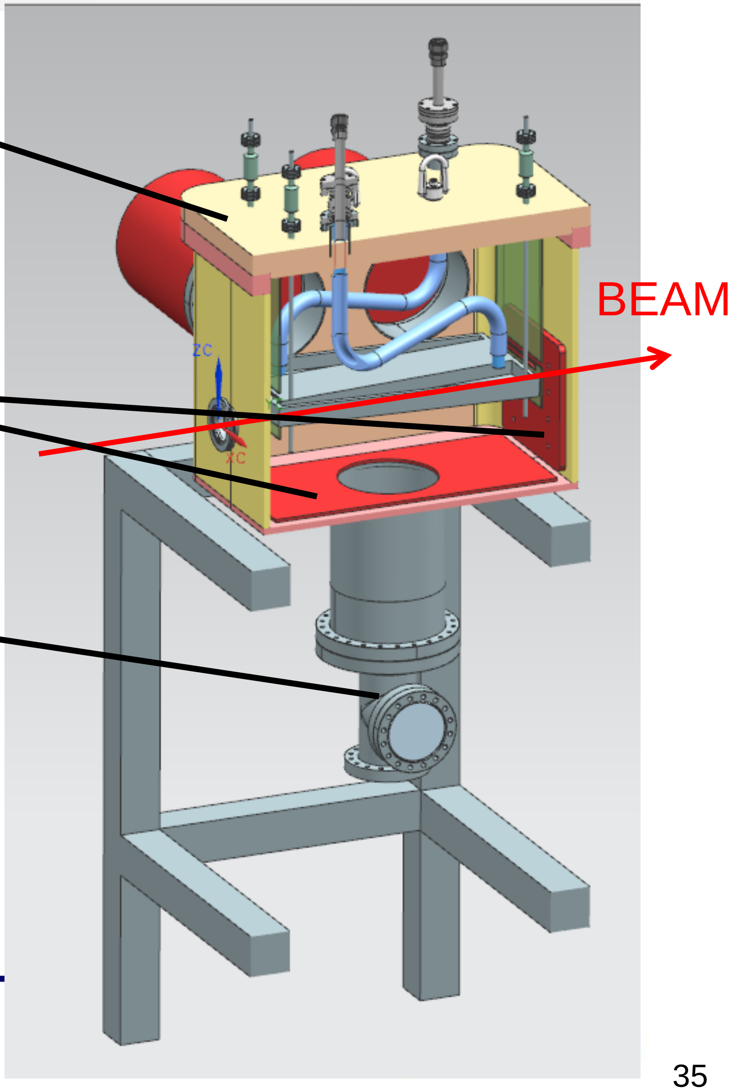
- A second prototype has been built and tested to PXIE power density and thermal cycling requirements, and has survived
- We're satisfied with the performance and details of this design, and know how to approach the implementation of the full-length absorber for PXIE
- H- induced sputtering and blistering is an open risk, and can only be practically tested in PXIE
- This existing prototype may be used to absorb up to ~5kW in early configurations of the MEBT

Next Steps: PXIE Implementation Assembly Cartoon

Absorber kinematically mounted
on handling flange
Absorber is electrically isolated

Secondary absorbing plates
Intercept reflected particles

Placeholder for imaging system
Periscope arrangement
Inadequate as shown
(can’t image the full absorber surface)



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Contributors

Contributors

- K. Carlson - test stand electrical
- L. Carmichael – Thermal cycling program
- A. Chen – absorber vacuum
- A. Denisov – Scraper Measurements
- Yu. Eidelman – material choice
- C. Exline– prototype assembly
- M. Hassan – first concept
- R. Kellett – prototype assembly
- K. Kendziora – installation
- D. Lambert – installation
- V. Lebedev - first concept
- A. Mitskovets- test stand commissioning
- L. Prost – test stand, simulations
- R. Thurman-Keup- imaging
- J. Walton – test stand, pre-prototype

Thanks to

- V. Dudnikov
  Importance of blistering
- A. Lumpkin
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- V. Scarpine
  Help with optical measurements
- T. Schenkel
  Large reflected power for H-
- I. Terechkine
  Suggestion to use microchannels